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Hydrothermal monitoring in Yellowstone National Park using airborne thermal infrared remote sensing

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ABSTRACT

This paper describes the image acquisition and processing methodology, including surface emissivity and atmospheric corrections, for generating surface temperatures of two active hydrothermal systems in Yellowstone National Park. Airborne thermal infrared (8–12 μm) images were obtained annually from 2007 to 2012 using a FLIR SC640 thermal infrared camera system. Thermal infrared image acquisitions occurred under clear-sky conditions after sunset to meet the objective of providing high-spatial resolution, georectified imagery for hydrothermal monitoring. Comparisons of corrected radiative temperature maps with measured ground and water kinetic temperatures at flight times provided an assessment of temperature accuracy. A repeatable, time-sequence of images for Hot Spring Basin (2007–2012) and Norris Geyser Basin (2008–2012) documented fracture-related changes in temperature and fluid flow for both hydrothermal systems, highlighting the utility of methods for synoptic monitoring of Yellowstone National Park's hydrothermal systems.

1. Introduction

Established in 1872, Yellowstone National Park is famous for its globally rare collection of hydrothermal features - geysers, mud pots, steam vents, and hot springs. An unusual heat source, cold groundwater recharge, and a natural network of fluid flow pathways are necessary for these composite natural resources - hydrothermal features and the hydrothermal system. The U.S. Congress requires the monitoring of Yellowstone's hydrothermal system. Protection of Yellowstone National Park's hydrothermal systems involves the utilization of scientific information and knowledge about the geologic processes responsible for their occurrence.

Beginning in 2007, an airborne thermal infrared (TIR) monitoring technique was used to gather night baseline data for hydrothermal systems within Yellowstone National Park (YNP) using a FLIR SC640, broad-band (8–12 μm) TIR camera flown at 1800 m above ground level. Airborne image acquisition occurred during night and yielded uncorrected temperature images with 1-m spatial resolution. Fall and spring acquisitions minimized solar heating effects. Fall acquisitions also minimized the ground cooling effect of melting snow. Calibration and corrections for atmospheric effects in the imagery as well as emissivity of the ground resulted in temperature maps of the hydrothermal systems. Comparing derived radiative temperatures with ground temperatures of hydrothermal pools provided an assessment of the monitoring technique's thermal accuracy for various temperatures.

Remote sensing techniques have proven to be an effective means to monitor the Park's hydrothermal systems. These techniques complement geochemical monitoring, (Friedman, 2007), helicopter condition assessments of hydrothermal areas, and field studies. The goal of airborne acquisition was night TIR imagery with 1-m spatial resolution and 1 °C temperature accuracy. A 1-m spatial resolution permitted the detection of spatial change in a 1-m pool or area of ground. High-spatial resolution also enabled the detection and monitoring of hydrothermal changes within a short time frame such as 1-year or less. A 1 °C temperature accuracy will enable future radiative heat flow calculations with the desired accuracy. Airborne TIR remote sensing fills a niche between ground or helicopter reconnaissance and satellite-based remote sensing. Although TIR satellite imagery (Landsat, ASTER and MODIS) covers large areas effectively, the spatial resolution is too coarse (60 to 1000 m per pixel) for the detailed monitoring of changing hydrothermal systems.

Satellite-based remote sensing in the TIR part of the spectrum has been used to estimate surface energy balance components and evapotranspiration over large agricultural areas (Bastiaansen, Menenti, Feddes, & Holtslag, 1998; Kustas & Norman, 1999; Li, Kustas, Prueger, Neale, & Jackson, 2005; Taghvaeian & Neale, 2011) and monitor urban areas (Roberts, Quattrochi, Hulley, Hook, & Green, 2012). Satellite studies in YNP have (1) modeled snow-free areas using Landsat (Watson,

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Lockwood, Newman, Anderson, & Garrott, 2008), (2) used Landsat summer imagery for park-wide monitoring of geothermal areas (Savage et al., 2010) and (3) used night ASTER and MODIS imagery for monitoring geothermal activity as well as estimating park-wide radiant geothermal heat flow (Vaughan, Kezthelyi, Lowenstern, Jaworowski, & Heasler, 2012). A recent literature review (Li et al., 2013) highlighted the challenges in extracting land surface temperatures from satellite sensors. Previous airborne remote sensing applications involved assessing water temperatures in rivers and streams (Torgesen, Faux, Mcintosh, Poage, & Norton, 2001) and estimating surface parameters (Quatrtrochi & Luvall, 2003).

This paper describes a TIR methodology for acquiring and processing baseline imagery used for monitoring two hydrothermal systems in Yellowstone National Park: Hot Spring Basin (HSB) and Norris Geyser Basin (NGB) (Fig. 1). These two hydrothermal systems were chosen because there was a possibility of significant surface temperature changes during the multi-year period of this study. Significant changes in the ground surface temperature at HSB may be expected to occur over a

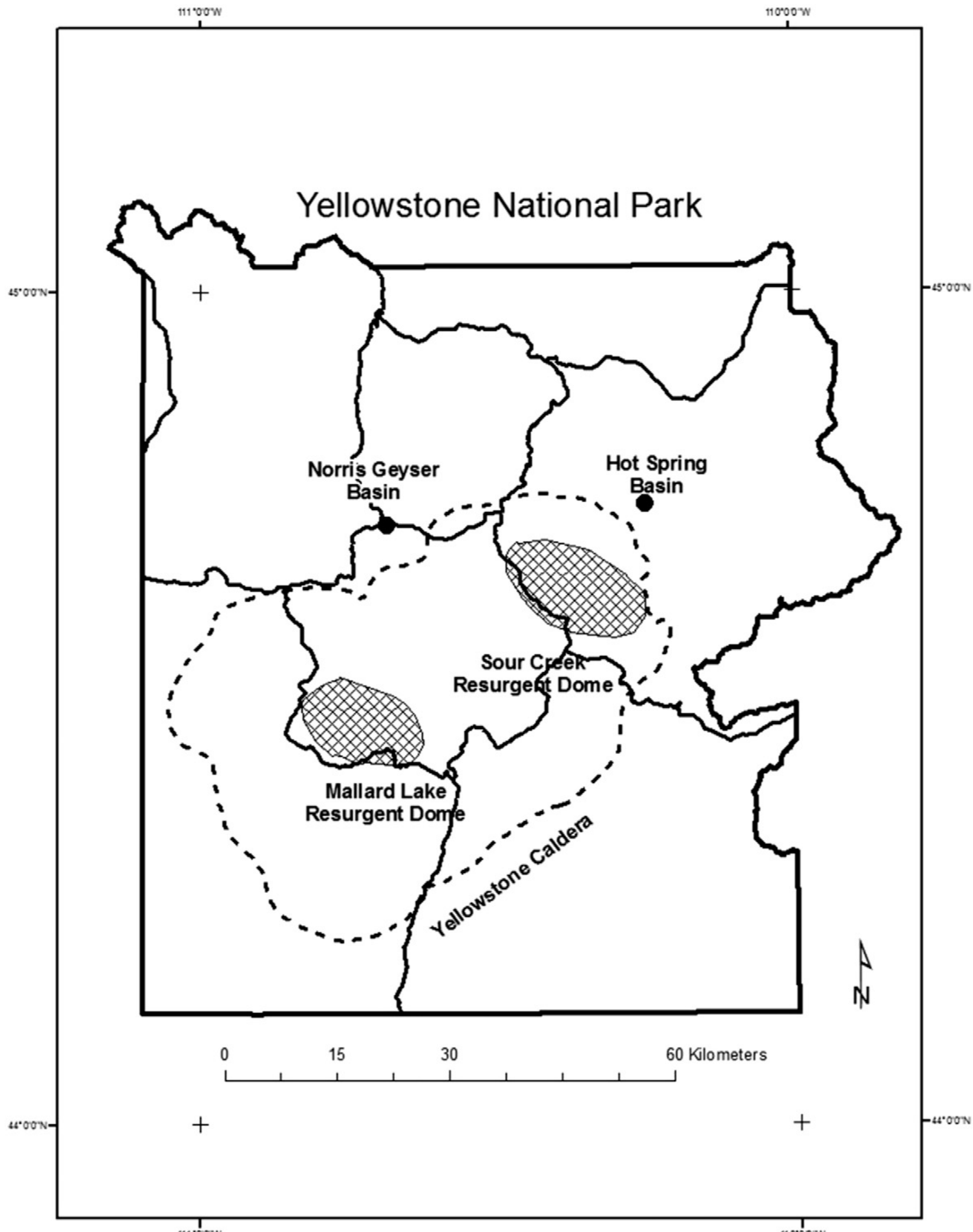

Fig. 1. Map showing location of NGB and HSB hydrothermal systems (black dots) within Yellowstone National Park. The map also highlights major roads (solid black lines), the 640,000 year-old Yellowstone caldera (black dashed line) and two resurgent domes (Mallard Lake and Sour Creek; cross-hatched areas). Geologic data from Christiansen (2001) and other digital information from NPS Data Store (http://www.nps.gov/gis/, accessed 17 September 2014).